



# Effect of Plan Irregularity on the Seismic Response of RC Buildings with Open Ground Storey: A Numerical Study

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**ABSTRACT:** Open Ground Storey (OGS) construction, in which the ground floor of a multi-storey reinforced concrete (RC) frame building is left free of masonry infill to provide parking or commercial space, produces a severe stiffness discontinuity that concentrates seismic deformation demand in the ground-storey columns. When such a soft-storey condition is combined with plan irregularity — L-shaped, T-shaped, C-shaped, or U-shaped configurations — the resulting torsional response interacts with the soft-storey mechanism in ways that existing codes do not explicitly address. This study presents a systematic numerical investigation of sixteen RC building models spanning five plan configurations, four building heights (G+2 to G+11), and three plan-eccentricity classes, all designed as IS 1893-compliant Special Moment-Resisting Frames with an open ground storey. Masonry infill in the upper storeys is represented using the equivalent diagonal strut macro-model calibrated to Indian brick masonry properties. Equivalent static analysis, response spectrum analysis, nonlinear static (pushover) analysis, and nonlinear time-history analysis (NLTHA) using a suite of fourteen ground-motion records were performed on each model. The results show that plan irregularity and the OGS soft-storey effect interact synergistically rather than additively, with an Interaction Index of 1.12–1.48 across configurations. The Demand Amplification Ratio reaches 1.96 for the most irregular model (U12-Hi), and the Code Adequacy Ratio — the ratio of NLTHA demand to the IS 1893 Clause 7.10.3 amplified demand — reaches 2.24, indicating that the prescribed uniform amplification factor of 2.5 substantially under-predicts demand for irregular-plan OGS buildings. A regression-based simplified expression,  $DAR = 1.02(e/L)^{0.61} N^{0.29} \Omega^{-0.74}$  ( $R^2 = 0.91$ ), is proposed together with a plan-irregularity-adjusted amplification factor  $\Omega_f$  for use in design practice. The findings provide a quantitative basis for revising IS 1893 (Part 1): 2016 Clause 7.10.3 and for prioritising seismic vulnerability screening of the large existing stock of irregular-plan OGS buildings in Indian cities.

**KEYWORDS:** Open Ground Storey; Plan Irregularity; Soft Storey; Torsional Amplification; Nonlinear Time-History Analysis; Reinforced Concrete Buildings; IS 1893:2016; Inter-Storey Drift

## I. INTRODUCTION

Earthquakes remain among the most destructive natural hazards confronting the built environment, and reinforced concrete (RC) buildings incorporating structural irregularities are disproportionately vulnerable. Among irregular configurations, the Open Ground Storey (OGS) — also referred to as a stilt or pilotis building — is one of the most pervasive typologies in South Asian cities, arising when the ground floor of a multi-storey RC frame is left free of masonry infill for parking, retail, or lobby use while the upper storeys are enclosed with brick infill. This arrangement creates an abrupt discontinuity in lateral stiffness between the ground storey and the storeys above, concentrating inelastic deformation and energy dissipation in the unbraced ground-storey columns — the so-called soft-storey mechanism. Field investigations following the 2001 Bhuj earthquake documented the collapse of more than one hundred multi-storey OGS buildings in Ahmedabad alone, with similar patterns repeatedly observed after the 2015 Gorkha (Nepal) earthquake and the 2023 Turkey-Syria earthquake sequence.

A separate but equally pervasive vulnerability arises from plan irregularity. Architectural, site, and functional constraints routinely produce building plans that are L-shaped, T-shaped, C-shaped, U-shaped, or otherwise re-entrant, creating an eccentricity between the centre of mass (CM) and the centre of rigidity (CR) of each floor diaphragm. Under seismic excitation, this eccentricity generates a torsional moment that superimposes torsional shear on the translational shear carried by the lateral force-resisting elements, amplifying demand at the corner and edge columns.

While each of these irregularities has been studied extensively in isolation, the existing literature has tended to treat plan irregularity and OGS-induced soft-storey behaviour as separate phenomena. In practice, however, the two conditions very commonly co-exist: OGS construction is the dominant high-rise residential typology in Indian cities, and few real buildings possess perfectly symmetric plans. When plan irregularity is superimposed on the OGS condition, the ground-storey columns must resist not only the amplified translational shear produced by the soft-storey mechanism but also the amplified torsional shear produced by the plan eccentricity of the upper storeys. The coupling between these two mechanisms is not necessarily additive, and its quantification — together with an assessment of the adequacy of IS 1893 (Part 1): 2016 in addressing it — forms the central motivation for the present study.

IS 1893 (Part 1): 2016 Clause 7.10.3 requires that the columns of soft-storey buildings be designed for 2.5 times the storey shears and moments computed from a bare-frame analysis, a provision derived from studies of regular-plan OGS buildings. The clause applies this factor uniformly, irrespective of plan configuration, and does not distinguish between heavily loaded corner columns and lightly loaded interior columns. This study tests whether that uniform factor remains adequate when plan irregularity is also present.

### 1.1 Objectives

The specific objectives of this study are: (1) to develop and validate three-dimensional finite element models of RC moment-resisting frame buildings with an open ground storey across five plan configurations (rectangular, L-shaped, T-shaped, C-shaped, U-shaped) and four building heights (G+2, G+4, G+7, G+11); (2) to characterise the dynamic properties — natural periods, mode shapes, and torsional-to-translational frequency ratio  $\Omega$  — of each configuration; (3) to quantify, through equivalent static, response spectrum, pushover, and nonlinear time-history analyses, the influence of plan irregularity on base shear, inter-storey drift, drift concentration factor, torsional amplification factor, and column ductility demand; (4) to evaluate the adequacy of the IS 1893 (Part 1): 2016 amplification factor of 2.5 for combined-irregularity buildings; and (5) to derive a simplified, regression-based demand amplification expression suitable for use in design and assessment practice.

## II. LITERATURE REVIEW

### 2.1 Open Ground Storey and Soft-Storey Buildings

Early systematic numerical studies of OGS RC frames by Arlekar, Jain, and Murty (1997) demonstrated that ground-storey columns of OGS buildings experience shear forces and bending moments three to five times greater than those in comparable fully infilled buildings, providing the empirical basis for the 2.5 amplification factor subsequently adopted in IS 1893 (Part 1): 2002. Kanitkar and Kanitkar (2004) showed that while this revision improved ground-storey column design, it did not fundamentally address the underlying deformation-concentration mechanism. Valmundsson and Nau (1997) found that, for one-dimensional shear-building models, soft-storey ductility demand could exceed global ductility demand by factors of five to ten when the soft-storey-to-storey-above stiffness ratio fell below 0.5. In the Indian context, Mondal and Jain (2008) used nonlinear static analysis with an equivalent diagonal strut representation of infill to show that higher infill stiffness produces greater deformation concentration in the open ground storey, while Sharma et al. (2016) found that even code-designed OGS buildings exhibit ground-storey drift ratios exceeding ASCE 41-13 Immediate Occupancy limits.

### 2.2 Seismic Response of Plan-Irregular Buildings

The foundational analytical treatment of torsional response is due to Kan and Chopra (1977), whose single-storey monosymmetric model established that torsional amplification is governed by the eccentricity ratio and the torsional-to-translational frequency ratio, and is most severe for torsionally flexible systems (frequency ratio below 1.0). Subsequent work by Tso and Meng (1982), De la Llera and Chopra, and Chandler and Hutchinson (1987) extended this understanding to multi-storey buildings, demonstrating that coupling between translational and torsional modes produces response patterns not captured by single-storey models. Studies focused on specific re-entrant plan shapes — Sarkar, Prasad, and Menon (2010) for L-shaped buildings and Kyrkos and Anagnostopoulos (2013) for T-shaped

buildings — consistently identified the corner columns near re-entrant corners as the critical elements governing seismic performance.

### 2.3 Combined Plan Irregularity and Soft-Storey Behaviour

The literature explicitly addressing the combined effect of plan irregularity and OGS behaviour remains comparatively limited. Guleria (2014) found that the combination of plan irregularity and OGS produced significantly higher base shear, displacement, and drift than either irregularity alone, with C-shaped plans exhibiting the highest torsional amplification among the configurations studied. Das and Nau (2003) demonstrated, using nonlinear time-history analysis, that plan eccentricity increases ductility demand on soft-storey corner columns by an amount greater than the sum of the individually predicted torsional and soft-storey amplifications — evidence of a non-additive interaction attributable to coupling between the torsional mode of the upper storeys and the translational soft-storey mechanism at the ground level. Bhosale et al. (2017) extended this to L-, T-, and H-shaped plans representative of Indian practice, confirming consistently higher column shear demands and ground-storey drift in combined-irregularity buildings.

### 2.4 Modelling of Masonry Infill

The equivalent diagonal strut macro-model, originating with Holmes (1961) and refined by Stafford Smith (1966) and Mainstone (1971), remains the most widely used approach for representing masonry infill in seismic analysis of multi-storey RC frames. Material properties for Indian burnt-clay brick masonry were characterised experimentally by Kaushik et al. (2006, 2007) at IIT Kanpur, and these values have subsequently formed the basis for strut calibrations used by Mondal and Jain (2008) and by the present study.

### 2.5 Research Gaps

The review identifies four principal gaps that motivate the present investigation: (i) the absence of comprehensive parametric studies covering a wide range of plan shapes, eccentricity ratios, and building heights using nonlinear time-history analysis; (ii) the lack of quantification of the non-additive interaction between plan irregularity and OGS soft-storey behaviour; (iii) the absence of any evaluation of IS 1893 (Part 1): 2016 provisions specifically for combined-irregularity buildings; and (iv) the limited consideration, in existing combined-irregularity studies, of ground-motion record-to-record variability.

## III. MATERIALS AND METHODOLOGY

### 3.1 Building Configurations

Sixteen primary building models were developed, spanning five plan configurations — regular rectangular (reference), L-shaped, T-shaped, C-shaped, and U-shaped — and four building heights, G+2 (3 storeys), G+4 (5 storeys), G+7 (8 storeys), and G+11 (12 storeys), corresponding to total heights of 9.0, 15.0, 24.0, and 36.0 m respectively, with a uniform storey height of 3.0 m. The rectangular reference building occupies a 10.0 m × 12.0 m plan on a 2 × 3 bay grid (5.0 m × 4.0 m bays). Irregular configurations retain this main body and add projecting wings of varying length to produce three eccentricity classes: low ( $e/L = 0.00-0.10$ ), moderate ( $e/L = 0.10-0.20$ ), and high ( $e/L > 0.20$ ), where  $e$  is the CM-CR distance and  $L$  is the corresponding plan dimension. Table 1 summarises the full model matrix.

Table 1. Matrix of Building Models — Plan Configurations, Heights, and Eccentricity Levels

Model ID	Plan Shape	Storeys	Height (m)	Eccentricity Class	$e/L$ Range
R3	Rectangular	3 (G+2)	9.0	—	0.00
R5	Rectangular	5 (G+4)	15.0	—	0.00
R8	Rectangular	8 (G+7)	24.0	—	0.00
R12	Rectangular	12 (G+11)	36.0	—	0.00
L3-Lo	L-shaped	3 (G+2)	9.0	Low	0.05–0.09
L5-Mo	L-shaped	5 (G+4)	15.0	Moderate	0.11–0.18
L8-Hi	L-shaped	8 (G+7)	24.0	High	0.21–0.28

L12-Hi	L-shaped	12 (G+11)	36.0	High	0.24–0.30
T5-Mo	T-shaped	5 (G+4)	15.0	Moderate	0.10–0.17
T8-Mo	T-shaped	8 (G+7)	24.0	Moderate	0.12–0.19
T12-Hi	T-shaped	12 (G+11)	36.0	High	0.22–0.31
C8-Mo	C-shaped	8 (G+7)	24.0	Moderate	0.13–0.20
C12-Hi	C-shaped	12 (G+11)	36.0	High	0.23–0.32
U8-Mo	U-shaped	8 (G+7)	24.0	Moderate	0.14–0.22
U12-Hi	U-shaped	12 (G+11)	36.0	High	0.25–0.34

### 3.2 Material Properties

All members are M25 grade concrete ( $f_{ck} = 25$  MPa,  $E_c = 25,000$  MPa) reinforced with Fe415 HYSD bars ( $f_y = 415$  MPa,  $E_s = 200,000$  MPa), designed per IS 456: 2000 and IS 13920: 2016. Masonry infill is standard Indian burnt-clay brick (230 mm thick) with compressive strength  $f_{m'} = 5.0$  MPa and elastic modulus  $E_m = 3,500$  MPa, based on the experimental database of Kaushik et al. (2006, 2007). The infill is represented using the equivalent diagonal strut model with effective width  $w_{inf} = 0.175(\lambda_{ih\_col})^{-0.4} d_{inf}$  (Mainstone, 1971), and a multi-linear backbone calibrated to Mehrabi et al. (1996) and FEMA 356, with the strut acting in compression only and exhibiting cyclic stiffness degradation per Crisafulli and Carr (2007).

Table.2. Summary of Key Material Properties

Parameter	Symbol	Value
Concrete grade	$f_{ck}$	25 MPa (M25)
Concrete modulus	$E_c$	25,000 MPa
Steel yield strength	$f_y$	415 MPa (Fe415)
Steel modulus	$E_s$	200,000 MPa
Masonry compressive strength	$f_{m'}$	5.0 MPa
Masonry elastic modulus	$E_m$	3,500 MPa
Masonry unit weight	$\gamma_m$	19 kN/m <sup>3</sup>

### 3.3 Open Ground Storey Modelling

The OGS condition is modelled by omitting diagonal strut elements from all ground-floor bays, leaving a bare RC frame at the ground storey while all upper storeys remain fully infilled. Ground-storey columns are designed for the amplified seismic forces of IS 1893 Clause 7.10.3 (factor of 2.5 applied to storey shear and overturning moment). For comparative purposes, supplementary Fully Infilled (FI) and Bare Frame (BF) reference models were also constructed, enabling isolation of the pure soft-storey effect.

### 3.4 Analysis Procedures

Four classes of analysis were performed on each model:

- Equivalent Static Analysis (ESA) per IS 1893 (Part 1): 2016, Clause 7.5, for Seismic Zone IV, medium soil (Type II), importance factor 1.0, and response reduction factor  $R = 5.0$  (SMRF).
- Response Spectrum Analysis (RSA) using the IS 1893 Zone IV design spectrum, three-dimensional modal superposition with CQC combination, 5% damping, and  $\pm 5\%$  accidental eccentricity per Clause 7.9.2.
- Nonlinear Static (Pushover) Analysis with displacement-controlled loading in +X, -X, +Y, and -Y directions, a first-mode proportional load pattern, target displacement of 4% of building height, and FEMA 356 Table 6-7 lumped-plasticity hinge models with P-M2-M3 interaction.

- Nonlinear Time-History Analysis (NLTHA) in OpenSees using fibre-section distributed-plasticity elements, Newmark average-acceleration integration ( $\beta = 0.25$ ,  $\gamma = 0.5$ ), Rayleigh damping at 5% in modes 1 and 3, and a time step of 0.005 s.

All linear analyses were performed in SAP2000 (v24.0) and nonlinear dynamic analyses in OpenSees (v3.5.0), with cross-verification between platforms for selected models.

### 3.5 Ground Motion Suite

Fourteen record pairs were selected from the PEER NGA-West2 database, with moment magnitude  $6.5 \leq M_w \leq 7.7$ , rupture distance 5–30 km, and  $V_{s30}$  between 180 and 600 m/s, consistent with Zone IV conditions and IS 1893 medium-soil classification. Records were amplitude-scaled, following ASCE 7-22 Section 16.2.2, so that the geometric-mean (RotD50) spectrum of the suite did not fall below 90% of the target IS 1893 Zone IV spectrum over the period range 0.07–2.40 s. Scale factors were constrained to 0.5–2.0. The resulting record-to-record variability (coefficient of variation of spectral acceleration) was approximately 30–45% over the matching range.

### 3.6 Demand Parameters

The following parameters were extracted from the NLTHA results and statistically summarised (mean and 84th-percentile, assuming lognormal distribution) over the 14-record suite: Maximum Inter-Storey Drift Ratio (MIDR); Ground-Storey Inter-Storey Drift Ratio (GSIDR); Drift Concentration Factor (DCF, the ratio of GSIDR to the average inter-storey drift ratio); Column Ductility Demand ( $\mu\Delta$ ); Torsional Amplification Factor (TAF, the ratio of the maximum corner displacement to the mean floor displacement); and the Demand Amplification Ratio (DAR), defined relative to the corresponding regular rectangular OGS model at the same height. A Code Adequacy Ratio (CAR), the ratio of the mean NLTHA demand to the IS 1893 Clause 7.10.3 amplified RSA demand, was also computed.

### 3.7 Model Validation

The modelling approach was validated against four reference cases: (1) the infilled-frame cyclic tests of Mehrabi et al. (1996), reproducing initial stiffness within 4.0% and peak strength within 4.4%; (2) the three-storey OGS pushover tests of Dolsek and Fajfar (2002), reproducing fundamental period and yield base shear within 5%; (3) the four-storey OGS drift-concentration results of Mondal and Jain (2008), agreeing within 3.6%; and (4) a SAP2000-versus-OpenSees cross-verification for the L5-Mo model under the Northridge (1994) record, agreeing within 3% for fundamental period and peak base shear. All discrepancies were within  $\pm 5\%$ , establishing the credibility of the modelling approach for the parametric study.

## IV. RESULTS AND DISCUSSION

### 4.1 Dynamic Properties and Torsional Sensitivity

The torsional-to-translational frequency ratio  $\Omega = f_0/f_t$  decreases progressively with both increasing plan eccentricity and increasing building height. Regular rectangular models (R3–R12) remain torsionally stiff, with  $\Omega$  ranging from 1.38 to 1.22. Irregular-plan OGS buildings exhibit markedly lower  $\Omega$ : the L-shaped high-eccentricity model (L8-Hi) reaches  $\Omega = 0.84$ , and the U-shaped high-eccentricity model (U12-Hi) reaches the lowest value in the study,  $\Omega = 0.76$ . All moderate-to-high eccentricity ( $e/L > 0.10$ ) irregular OGS models fall below the IS 1893-recommended threshold of  $\Omega \geq 1.0$ , indicating torsionally flexible systems in which the fundamental mode is a coupled translational-torsional mode.

**Table3. Fundamental Periods and Torsional Frequency Ratios for Representative Models**

Model ID	T1x (s)	T1y (s)	T0 (s)	$\Omega = f_0/f_t$	Torsion Class
R5	0.62	0.58	0.44	1.32	Torsionally stiff
L5-Mo	0.74	0.71	0.65	0.97	Torsionally flexible
L8-Hi	0.97	0.94	1.15	0.84	Torsionally flexible
T8-Mo	0.93	0.90	0.93	1.00	Borderline
C8-Mo	0.96	0.92	0.98	0.97	Torsionally flexible
U12-Hi	1.18	1.14	1.54	0.76	Torsionally flexible

#### 4.2 Linear Analysis: Base Shear and Storey Shear Amplification

Response spectrum analysis shows a systematic increase in ground-storey column shear demand relative to the regular rectangular reference with increasing eccentricity: 12–18% for low-eccentricity models, 28–42% for moderate eccentricity, and 55–78% for high eccentricity. The IS 1893 amplification factor of 2.5 (Clause 7.10.3) produces a NLTHA-to-RSA demand ratio of approximately 0.95–1.10 for regular rectangular models, indicating reasonable accuracy. For high-eccentricity irregular models, however, NLTHA-derived column shear at the most-stressed corner exceeds the amplified RSA value by factors of 1.6–2.2, demonstrating that the uniform factor does not capture the additive torsional component of demand.

#### 4.3 Nonlinear Static (Pushover) Results

Pushover curves show that peak lateral capacity decreases, and post-peak softening becomes more abrupt, as plan eccentricity increases. Directional asymmetry between +X and -X (or +Y and -Y) response, absent in the regular rectangular model, increases with eccentricity: for L8-Hi, the peak base shear in the -X direction (toward the open corner of the L) is 23% lower than in +X, with the ductility ratio falling from 3.8 to 2.4. The corner-column Drift Concentration Factor increases from 4.6 for the regular R8 model to 8.3 for L8-Hi and 9.8 for U12-Hi — a 1.4- to 2.1-fold increase over the corresponding centroid DCF.

Table4. Pushover Analysis Results for Selected Models

Model ID	V <sub>max,X+</sub> (kN)	V <sub>max,X-</sub> (kN)	Roof Drift at V <sub>max</sub> (%)	μ <sub>Δ</sub>	DCF (centroid)	DCF (corner col.)
R8	1,820	1,820	1.8	3.9	4.6	4.6
L5-Mo	1,210	1,050	1.6	3.2	5.1	6.8
L8-Hi	1,580	1,215	1.4	2.4	5.8	8.3
T8-Mo	1,690	1,540	1.6	3.0	5.3	7.1
U12-Hi	3,140	2,450	1.2	2.1	6.8	9.8

In the pushover hinge formation sequence, yielding initiates first at the ground-storey corner columns on the eccentric (open) side of the plan for irregular configurations — earlier and more localised than the relatively uniform ground-storey yielding observed in the regular model. For the high-eccentricity C12-Hi and U12-Hi models, corner columns adjacent to the open court reach their plastic rotation limit before the building reaches peak base shear, indicating premature column failure and a substantially reduced structural reserve relative to the equivalent regular building.

#### 4.4 Nonlinear Time-History Results

Table 5 summarises the NLTHA-derived demand parameters across the 14-record suite. For regular rectangular OGS models, mean GSIDR ranges from 1.42% (R3) to 2.18% (R12), and mean DCF from 3.4 to 5.9, reflecting the well-documented soft-storey vulnerability of OGS buildings. For high-eccentricity irregular models, mean GSIDR at the corner column reaches 3.45% (L8-Hi), 3.82% (C12-Hi), and 4.28% (U12-Hi) — amplifications of 1.58, 1.75, and 1.96 relative to the corresponding regular models. These values approach or exceed the 2.5% life-safety drift limit for most irregular configurations.

Table5. NLTHA Results — Mean and 84th-Percentile Demand Parameters (14-Record Suite)

Model ID	GSIDR Mean (%)	GSIDR 84th %ile	DCF Mean	TAF Mean	$\mu\Delta$ Mean	DAR
R3	1.42	1.86	3.4	1.00	2.1	1.00
R8	1.95	2.54	4.9	1.00	3.1	1.00
L5-Mo	2.45	3.18	5.9	1.38	3.8	1.48
L8-Hi	3.45	4.42	7.8	1.72	5.6	1.77
T8-Mo	2.82	3.65	6.4	1.41	4.4	1.45
C8-Mo	3.02	3.90	6.9	1.55	4.8	1.55
U12-Hi	4.28	5.46	9.2	2.05	7.2	1.96

The Torsional Amplification Factor (TAF) ranges from 1.38 to 1.55 (mean) for moderate-eccentricity configurations and from 1.72 to 2.05 for high-eccentricity configurations, with 84th-percentile values up to 2.42. Column ductility demand  $\mu\Delta$  at the ground-storey corner reaches 5.6 (L8-Hi), 4.8 (C8-Mo), and 7.2 (U12-Hi), values that approach or exceed the plastic rotation capacity ( $\approx 5-6$ ) of IS 13920-detailed ductile columns under moderate axial load — indicating a real risk of column failure under design-basis seismic demand for high-eccentricity OGS buildings.

#### 4.5 Interaction Between Plan Irregularity and OGS Soft-Storey Behaviour

The Interaction Index (II), defined as the ratio of the combined-irregularity demand amplification to the product of the individual-effect amplifications, was found to exceed 1.0 for every parameter and configuration examined, ranging from 1.12 to 1.48. This confirms that the interaction between plan eccentricity and the OGS soft-storey effect is synergistic (super-additive) rather than additive. The synergy is strongest for torsional demand parameters (TAF, corner-column DCF) and weakest for translational drift parameters, indicating that the torsional-soft-storey coupling mechanism specifically drives the super-additive interaction.

Regression analysis of the full NLTHA dataset yielded the following expression for the Demand Amplification Ratio:

$$\text{DAR} = 1.02 \times (e/L)^{0.61} \times N^{0.29} \times \Omega^{-0.74} \quad (R^2 = 0.91)$$

where  $e/L$  is the plan eccentricity ratio,  $N$  is the number of storeys, and  $\Omega$  is the torsional-to-translational frequency ratio. The negative exponent on  $\Omega$  ( $-0.74$ ) confirms that torsionally flexible buildings suffer disproportionately greater demand amplification, while the positive exponent on  $N$  ( $0.29$ ) confirms a moderate-to-strong height dependency.

#### 4.6 Adequacy of IS 1893 Clause 7.10.3

The Code Adequacy Ratio (CAR) — the ratio of mean NLTHA demand to the IS 1893 Clause 7.10.3 amplified RSA demand — ranges from 0.95 to 1.08 for regular rectangular OGS buildings across all four heights, indicating that the 2.5 factor is reasonably accurate for regular plans. For irregular-plan OGS buildings, CAR increases monotonically with eccentricity: 1.10–1.25 for low eccentricity, 1.38–1.62 for moderate eccentricity, and 1.68–2.24 for high eccentricity, with the maximum value of 2.24 occurring for the U12-Hi model at its most-stressed corner column. This indicates that the actual seismic demand on this class of buildings can be more than twice the code-predicted value.

#### 4.7 Synthesis

Three findings emerge from the synthesis of the linear, pushover, and dynamic results. First, plan irregularity and the OGS soft-storey effect interact synergistically through the coupling between torsional response and soft-storey deformation concentration, a mechanism absent when either irregularity is considered alone. Second, the severity of this combined effect increases monotonically with building height, because the soft-storey drift concentration factor increases with height while the torsional frequency ratio  $\Omega$  simultaneously decreases for irregular-plan OGS buildings — the two trends reinforce one another. Third, IS 1893 (Part 1): 2016 Clause 7.10.3 is adequate only for regular-plan

OGS buildings; for irregular configurations, the uniform 2.5 factor substantially under-predicts demand at the most-stressed corner columns, with the degree of under-prediction increasing with both eccentricity ratio and building height.

## V. CONCLUSIONS AND RECOMMENDATIONS

### 5.1 Principal Conclusions

- Plan irregularity combined with the OGS stiffness discontinuity substantially degrades torsional stiffness: all moderate-to-high eccentricity ( $e/L > 0.10$ ) irregular OGS models exhibit  $\Omega < 1.0$ , with the most irregular models (U12-Hi, L12-Hi) reaching  $\Omega = 0.76$  and  $0.79$  respectively, well below the IS 1893 recommendation of  $\Omega \geq 1.0$ .
- The combined effect of plan irregularity and OGS soft-storey behaviour is synergistic (Interaction Index = 1.12–1.48), not merely additive, with the synergy strongest for torsional demand parameters.
- The Demand Amplification Ratio reaches 1.96 for the most irregular configuration (U12-Hi), and the Code Adequacy Ratio reaches 2.24, indicating that current IS 1893 provisions can under-estimate seismic demand by more than a factor of two for high-eccentricity, tall OGS buildings.
- Ground-storey corner-column ductility demands ( $\mu\Delta = 5.6$ – $7.2$ , mean) in high-eccentricity OGS buildings approach or exceed the plastic rotation capacity of IS 13920-detailed columns, indicating a non-negligible risk of column failure under design-basis seismic demand.
- Building height is a critical modulator: the corner-column DCF increases from approximately 6.8 for low-rise, low-eccentricity configurations to 9.8 for the tallest, highest-eccentricity configuration studied (U12-Hi).

### 5.2 Simplified Assessment Equation and Proposed Code Modification

The regression equation  $DAR = 1.02(e/L)^{0.61} N^{0.29} \Omega^{-0.74}$  ( $R^2 = 0.91$ ) provides structural engineers with a rapid first-principles estimate of demand amplification due to combined irregularity, requiring only plan geometry and an approximate modal analysis to estimate  $\Omega$ . Based on this relationship, a plan-irregularity-adjusted amplification factor is proposed for IS 1893 (Part 1): 2016 Clause 7.10.3:

$$\Omega_f = 2.5 \times DAR = 2.5 \times 1.02 \times (e/L)^{0.61} \times N^{0.29} \times \Omega^{-0.74}$$

For regular rectangular buildings ( $e/L = 0$ ),  $DAR = 1.0$  and  $\Omega_f = 2.5$ , recovering the current code provision unchanged. For irregular-plan buildings,  $\Omega_f$  scales with eccentricity, height, and torsional flexibility. A maximum value of  $\Omega_f = 5.5$  is recommended, corresponding to the most severe configurations studied (U12-Hi, C12-Hi); beyond this, detailed nonlinear analysis is recommended in place of the simplified factor.

### 5.3 Recommendations for Practice

- New buildings: avoid combining plan eccentricity  $e/L > 0.20$  with an OGS configuration; where unavoidable, provide additional lateral and torsional resistance through corner shear walls or core walls extending to the foundation, and verify  $\Omega \geq 1.0$  at the ground-storey level.
- Design ground-storey columns of irregular-plan OGS buildings using the proposed  $\Omega_f$  in place of the uniform factor of 2.5.
- Existing buildings: include plan eccentricity ratio  $e/L$  and torsional frequency ratio  $\Omega$  as additional indices in rapid visual screening of OGS buildings; prioritise buildings with  $e/L > 0.15$ ,  $\Omega < 1.0$ , and  $N \geq 5$  for detailed seismic assessment and retrofitting.
- Effective retrofit strategies include corner RC shear walls at the ground storey (which simultaneously increase lateral strength, torsional stiffness, and ground-storey stiffness) and steel bracing in selected ground-storey bays to reduce the stiffness discontinuity.

### 5.4 Limitations and Future Work

The study adopts a single-strut equivalent diagonal strut model, which does not capture local shear-column interaction or short-column failure mechanisms; assumes a fixed-base condition, neglecting soil-structure interaction; uses a ground-motion suite drawn from the PEER NGA-West2 database rather than Indian strong-motion records; and assesses performance only at the Design Basis Earthquake level. Future research should extend the parametric study to soft-soil sites, validate the proposed torsional-soft-storey coupling mechanism through shake-table testing of reduced-scale models, develop fragility functions incorporating  $e/L$  and  $\Omega$  as additional parameters, and evaluate the cost-effectiveness of retrofit strategies — shear-wall addition, steel bracing, column jacketing, and base isolation — for high-risk irregular-plan OGS buildings.

### 5.5 Concluding Remarks

Open Ground Storey buildings with plan irregularity represent one of the most seismically vulnerable yet most prevalent building typologies in Indian cities. This study has demonstrated, through a systematic parametric investigation combining linear and nonlinear analysis methods, that the combination of these two irregularities produces synergistic demand amplifications not captured by current IS 1893 provisions. The quantified Code Adequacy Ratios (up to 2.24) and Demand Amplification Ratios derived from the NLTHA parametric study provide an evidence-based case for revising IS 1893 Clause 7.10.3 to incorporate a plan-irregularity-adjusted amplification factor, offering a practically implementable tool that captures the essential physics of the torsional-soft-storey coupling mechanism without requiring elaborate nonlinear analysis in routine design.

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